Electrode pattern design for GaAs betavoltaic batteries*

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Abstract: The sensitivities of betavoltaic batteries and photovoltaic batteries to series and parallel resistance are studied. Based on the study, an electrode pattern design principle of GaAs betavoltaic batteries is proposed. GaAs PIN junctions with and without the proposed electrode pattern are fabricated and measured under the illumination of ^{63}Ni. Results show that the proposed electrode can reduce the backscattering and shadowing for the beta particles from ^{63}Ni to increase the GaAs betavoltaic battery short circuit currents effectively but has little impact on the fill factors and ideal factors.

Key words: betavoltaic; photovoltaic; electrode design; series and parallel resistance

DOI: 10.1088/1674-4926/32/8/084006 **EEACC:** 2520

1. Introduction

Betavoltaic batteries are attractive candidates for nano-power sources because of their long lifetime (tens of years) and super high energy density (tens times higher than that of lithium ion batteries), which hence have attracted more and more research attention in recent years[1−6]. The work principles of betavoltaic batteries and photovoltaic batteries are similar to each other for the same energy convertors: PN junctions. Some methods in researching photovoltaic batteries are used in betavoltaic batteries too, such as I–V characteristic analysis and electrode pattern design. Some reported betavoltaic batteries adopt the pectinate electrode that is widely used in photovoltaic batteries[7−9]. However, given the structures and output characteristic differences between photovoltaic batteries and betavoltaic batteries, the pectinate electrode may be not suitable for betavoltaic batteries. The backscattering and shadowing effect of the metal electrode will decrease the battery output power significantly. In 4H-SiC betavoltaic batteries, it was found that even a thin layer of Ni, 100 nm, can cause a 25% reduction in current multiplication when illuminated by a 17 keV electron beam[10]. Optimizing the electrode pattern to reduce the electrode area is very important for betavoltaic batteries.

The sensitivities of betavoltaic batteries and photovoltaic batteries to series and parallel resistance are studied theoretically and experimentally in this paper. The betavoltaic batteries are affected significantly by the parallel resistance, while little by the series resistance; photovoltaic batteries are just the opposite. Hence the electrode area for betavoltaic batteries should be smaller to reduce the backscattering and shadowing of the beta particles. GaAs junctions with pectinate and point electrodes are fabricated. The measured beta I–V characteristics show that a point electrode is preferred for GaAs betavoltaic batteries.

2. Sensitivities of betavoltaic batteries and photovoltaic batteries to series and parallel resistance

Electron–hole pairs are induced when photons or beta particles impact onto PN junctions. The induced electron–hole pairs in the depletion region will be collected by the build-in electric field causing the output current. Figure 1 shows the circuit model of betavoltaic batteries and photovoltaic batteries. The I–V characteristics of the batteries can be expressed by[11]

$$V = \frac{nkT}{q}\ln\left(\frac{I - V/R_{\mathrm{sh}}}{I_0} + 1\right) + IR_{\mathrm{s}}, \tag{1}$$

where V is the output voltage, n is the ideal factor, k is the Boltzmann constant, T is the absolute temperature, I is the output current, I_0 is the leakage current, R_{s} is the series resistance and R_{sh} is the parallel resistance.

The depletion region of the PN junction should be thick enough to collect electron–hole pairs as much as possible. For photovoltaic batteries, the thickness depends on the light absorption in the semiconductor, which can be expressed by

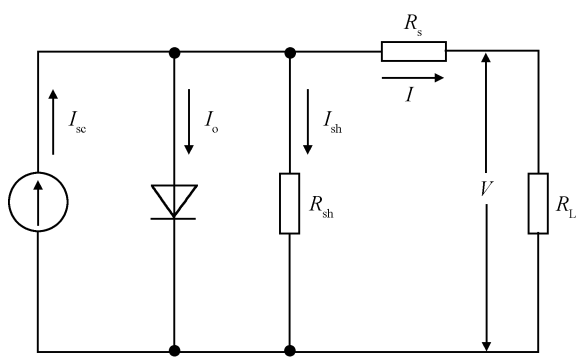

Fig. 1. Circuit model for betavoltaic and photovoltaic batteries.

* Project supported by the National Natural Science Foundation of China (Nos. 90923039 and 51025521) and the 111 Project of China (No. B08043).

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Received 11 February 2011, revised manuscript received 7 April 2011

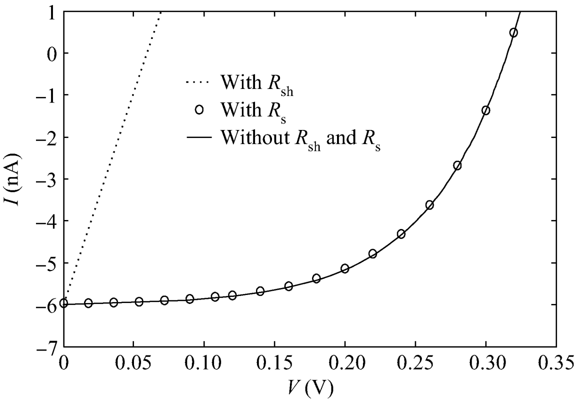

Fig. 2. Calculated I–V curves for GaAs junctions with R_s or R_{sh} under the illumination of ^{63}Ni.

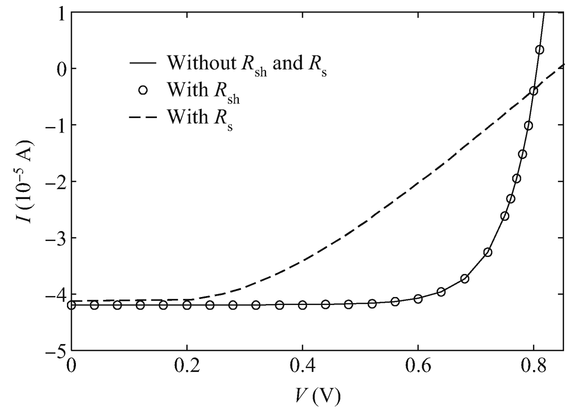

Fig. 3. Calculated I–V curves for GaAs junctions with R_s or R_{sh} under the illumination of light.

$$\phi = \phi_0 e^{-\alpha x}, \tag{2}$$

where ϕ_0 is the initial luminous flux, x is the thickness of the semiconductor layer, ϕ is the residual luminous flux after an x cm layer and α is the absorption factor. The GaAs bandgap is 1.43 eV. The absorption factor for a 1.43 eV photon is about 10^5 cm^{-1}. ϕ will be less than $0.1\phi_0$ after a 1 μm GaAs layer. Hence, the corresponding depletion region thickness of the GaAs PN junction should be about 1 μm. ^{63}Ni is widely used as the isotope source for betavoltaic batteries. Its energy spectrum $P(E)$ can be calculated by[12]

$$P(E) = \frac{g_{GT}^2 |M_{GT}|^2}{\pi^3 c^3 \hbar^7} F(Z, E)(E_m - E)^2 m E, \tag{3}$$

where g_{Gt} is a constant, M_{gt} is the nuclear matrix, $F(Z, E)$ is the coulomb modify coefficient, m is the electron mass, c is the velocity of light, $\hbar$ is Planck's constant, Z is the nuclear charge number, ρ is the GaAs density and E_m is the maximum energy of the ^{63}Ni energy spectrum.

The kinetic energies of beta particles emitted from ^{63}Ni range from 0 to 66.7 keV, with an average of 17.1 keV. The penetration depth of a 17.1 keV beta particle in GaAs is about 3 μm, which can be calculated in different ways, such as the models of continuous slowing-down approximation[13], Kanaya–Okayama (K–O)[14], Wittry–Kyser[15] and Everhart–Hoff[16]. So the depletion region thicknesses of ^{63}Ni illuminated GaAs betavoltaic batteries should be about 3 μm at least. The thicker depletion region implies that the internal resistances of GaAs betavoltaic batteries are greater than those of GaAs photovoltaic batteries. On the other hand, to avoid crystal defects in the semiconductor, an isotope source with low kinetic energy (tens to hundreds keV) beta particles should be chosen for betavoltaic batteries. Hence, the typical output current of a 1 × 1 cm^2 betavoltaic battery is about several to tens of nanoamperes. The low output current also induces higher internal resistances than those of a photovoltaic battery.

With higher internal resistances, the performance of betavoltaic batteries can be changed easily by parallel resistances but hardly by series resistances, which are very different with a photovoltaic battery. This can be seen from the calculated I–V curves of GaAs betavoltaic batteries and photovoltaic batteries with series resistance (10^7 Ω) or parallel resistance (10^4 Ω).

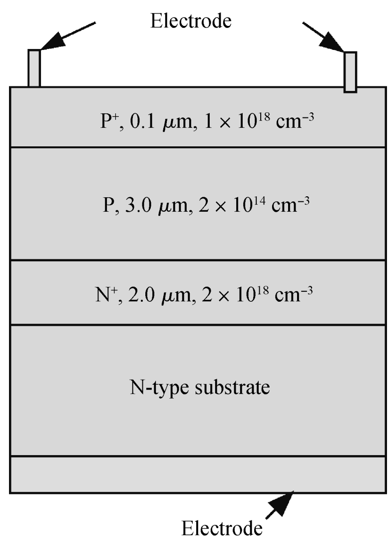

Fig. 4. Schematic structure of the GaAs junctions.

The curves are shown in Figs. 2 and 3. In the calculation, we let $n = 2.3$, $I_0 = 3 \times 10^{-11}$, $I_{sc} = 6 \times 10^{-9}$ A for ^{63}Ni illuminated GaAs junctions and $n = 2.2$, $I_0 = 3 \times 10^{-11}$, $I_{sc} = 42 \times 10^{-6}$ A for light illuminated GaAs junctions. These are typical values in our experiment.

3. Experiment

P^+PN^+ junctions are fabricated, and the schematic structures of the junctions are shown in Fig. 4. GaAs epilayers are grown by molecular beam epitaxy (MBE). Firstly, an N-type GaAs substrate with a doping concentration of 1 × 10^{18} cm^{-3} is cleaned in 100 ℃ ethanol, acetone and trichloroethylene for 5 min each and then in H_2SO_4–H_2O_2–H_2O (5 : 1 : 1) solution for 1 min. Secondly, the cleaned substrate is put in the sampling chamber and heated to 200 ℃ for 4 h and then in the epitaxy chamber. Lastly, GaAs epilayers are grown at 580 ℃ with a growth rate of 1 μm/h (P-type and N-type GaAs layers are doped with Zn and Si, respectively). The GaAs epilayers are good in uniformity and purity. The layer thickness can meet the design precision. Ohmic contacts are made by thermal evaporation of 500 Å Ni, 250 Å Ge and 1 μm Au (n-type contacts),

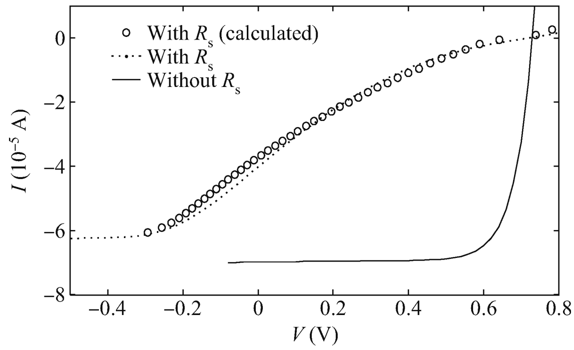

Fig. 5. Measured and calculated I–V curves for GaAs junctions with R_s or R_{sh} under the illumination of light.

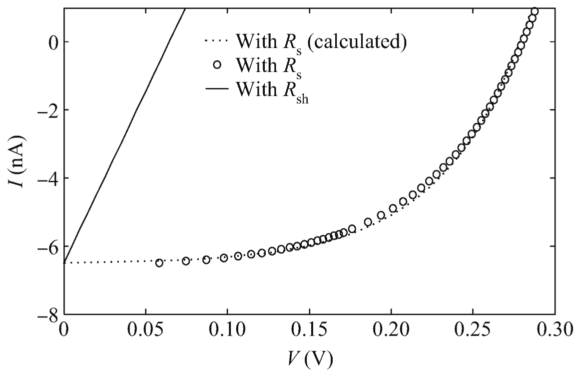

Fig. 6. Measured and calculated I–V curves for GaAs junctions with R_s or R_{sh} under the illumination of ^{63}Ni.

and they are alloyed at 600 ℃ and 100 Å Ni 150 Å Pt and 1 μm Au (p-type contacts), and they are alloyed at 440 ℃. A SiO_2 passivation layer of 500 Å is grown by PECVD at 300 ℃. The battery areas are 5 × 5 mm^2. 5 × 5 mm^2 ^{63}Ni with an activity of 10 mCi/cm^2 is used as a beta source.

The ohmic contact can't be realized all of the time for some uncontrollable factors. Sometimes, large series resistance can be found in the junctions. The following empirical formula is used to express the series resistance,

$$R = R_c + \frac{n_1 kT}{q}\frac{1}{|I| + I_{01}} + (-|I| + I_{sc}) \times 1 \times 1.4 \times 10^8, \quad (4)$$

where $R_c = 1.2 \times 10^4$ Ω, $n_1 = 2.5$ and $I_{01} = 7 \times 10^{-7}$ A.

4. Results and analysis

The I–V characteristics are tested in a sealed Faraday Cage using a Keithley 4200. The ^{63}Ni sources are placed close to the junction surfaces. A 40 W daylight lamp is used as the light source and it is fixed at a certain distance above the junctions (the lumen of the light doesn't need to be known because the light I–V curves are just used as rough comparisons).

The measured light I–V curves of junctions with and without ohmic contact are shown in Fig. 5. The measured beta I–V curves of junctions with and without parallel resistance (10^7 Ω) are shown in Fig. 6. It's worth mentioning that the beta I–V curves of junctions without ohmic contact are similar to those of the junctions with ohmic contact. Calculated bate and light

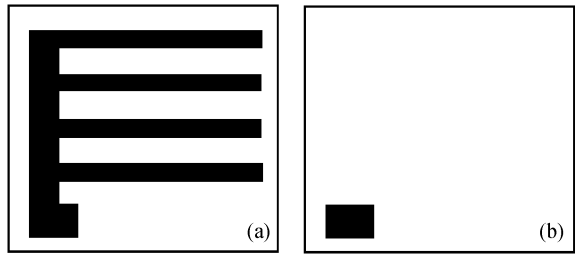

Fig. 7. Schematic patterns of (a) the pectinate electrode and (b) the point electrode.

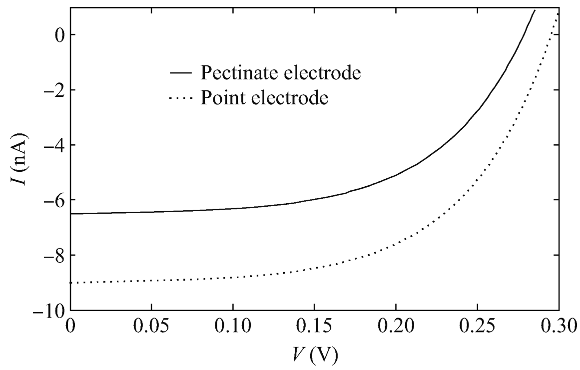

Fig. 8. The measured I–V curves of GaAs junctions with the pectinate and point electrodes.

I–V curves are also shown in Figs. 5 and 6 for comparison. The calculated curves agree well with the measured ones. This validates the aforementioned betavoltaic batteries' sensitivity to the series and parallel, and implies that the betavoltaic batteries are not strict in the quality of the electrode ohmic contact.

As the betavoltaic batteries are insensitive to series resistance, the electrode pattern can be simpler and the electrode area can be smaller. Then more beta particles will impact onto the GaAs junction and induce more electron-hole pairs causing greater short circuit currents.

40 prototype P^+PN^+ junctions in total (20 junctions with a pectinate electrode and 20 junctions with a point electrode) are fabricated. The areas of the pectinate and point electrode are 8 mm^2 and 0.16 mm^2, respectively. The electrode schematic patterns are shown in Fig. 7. The junctions are uniform in their characteristics. The typical measured beta I–V curves are shown in Fig. 8. Short circuit currents of junctions with the pectinate electrode and point electrode are about 6 nA and 9 nA, respectively. They are proportional to the junction uncovered areas. Compared with the battery with the pectinate electrode, the battery with the point electrode shows higher short circuit current but the same leakage current, fill factor and ideal factor.

5. Conclusion

Different from photovoltaic batteries, betavoltaic batteries are affected little by series resistance but significantly by parallel resistance, which is validated theoretically and experimentally. This means that a simple electrode pattern and small electrode area can be used in betavoltaic batteries. GaAs betavoltaic batteries with a pectinate electrode and a point electrode are fabricated and measured under the illumination of ^{63}Ni. The results show that the point electrode will lead to a higher short circuit current for the batteries but has no adverse effects.

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